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CUMULUS CONVECTION AND ITS INTERACTION WITH LARGER SCALES OF MOTION

by

Joseph Levine

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TECHNICAL REPORT

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Approved for Distribution

Claes G. H. Rooth
Assistant Chairman

ABSTRACT

The data reduction procedures used on the observations obtained from the ESSA Research Flight Facility aircraft during the Stormfury 1965 operation is described. The results to be obtained eventually are cloud liquid water content, volume median drop size, turbulent vertical velocity, and buoyancy fluctuations in cloud passes made by the aircraft.

DATA REDUCTION OF STORMFURY 1965 CLOUD OBSERVATIONS MADE FROM RESEARCH FLIGHT FACILITY AIRCRAFT

1. Introduction.

During the Stormfury 1965 expedition, several instrumented aircraft took part in a program for observing seeded and unseeded cumulus clouds. The writer was closely associated with the work of the two DC-6 aircraft of the ESSA Research Flight Facility, both of which were equipped with his hot wire instrument system for recording cloud liquid water content and volume median drop diameter. The outputs from this instrument system were recorded on oscillograph recorders along with the Johnson-Williams hot wire instrument, a fast response temperature (Rosemount) instrument, and a vertical accelerometer.

In addition, the digital magnetic tape recording system made records of many other quantities such as vortex thermometer temperature, absolute humidity, pressure, winds, and positon. To take full advantage of the aircraft instrument system, the writer had to find a way of combining the oscillograph recorded data with that of the digital system.

The writer's solution to the problem consisted of having the oscillograph records converted to punched cards with a Benson-Lehner Oscar S reader. Selected data from the edited magnetic tapes were transferred to new tapes by the National Hurricane Research Laboratory in Fortran II compatible format also compatible with the GE-225 Computer at the Woods Hole Oceanographic Institution. A program then was written to combine the cloud runs now recorded on punched cards with the corresponding data on magnetic tapes. Hereafter the magnetic tapes from the National Hurricane Research Laboratories will be referred to as "NHRL Stormfury 1965" tapes.

The combined punched card and tape data will be referred to hereafter as "WHOI Stormfury 1965 I" tapes. The tapes containing the liquid water content, volume median drop diameter, turbulent vertical velocity, and associated information derived from the aforementioned tapes will be referred to as "WHOI Stormfury 1965 II" tapes.

The context of the writer's work during the Stormfury 1965 operation may be seen in the preliminary and annual reports by Simpson, Simpson, Stinson, and Kidd (1965, 1966). In this context the writer's contribution consisted of a step in the direction of improved observational definition of clouds and their environment. The tools used were an amalgam of the writer's instrumentation with that of the Research Flight Facility combined with digital computer techniques for handling the large mass of data.

The present report consists of little more than the basic reduction of the data. More detailed analysis and conclusions from the data must yet be made. The fitting of the data into the overall context of the seeding experiment is the project supervisor's prerogative, but the writer considers interpretation of the data in terms of his model and modified forms of it as at least partially his prerogative.

2. Final version of calibration.

The maximum and volume median diameters (Levine, 1965) were plotted against water flow rate W in cc/min. for each value of air pressure P in lbs./ sq. in. Empirical equations were fitted to the data in such a way that extreme values were generally enveloped by the resultant straight lines for each nozzle air pressure. The results are summarized in Figures 1 and 2. The empirical equations fitted the data reasonably well except for the lowest pressure of 5 lb/sq. in. The anomalous behavior of the data at 5 lb/sq. in. probably was caused by settling out of the larger drops on the bottom bell mouth wall, which was observed to be badly wetted by the spray. At higher air pressures the wetting of the wall was negligible.

Then the empirical equations given in Figures 1 and 2 were used to obtain the maximum and volume median drop diameters contained in Table 1. The data in Table 1 were divided into 4 size groups as indicated by the zig-zag lines and averaged. This grouping made the wind tunnel data more manageable in the construction of calibrations. The average galvanometer current for each average liquid water content (determined from the flow rate) and drop-size group were evaluated and plotted. There was no systematic non-linear behavior apparent within the accuracy of the data. Therefore, straight lines through the origin for each drop-size group of the form

$$i = Sw \qquad (1)$$

were assumed, where i is the current (in microamps), w is the liquid water (gm per cubic meter), and S is a function of drop size, different for each of the two instruments.

Since the accuracy of w is much greater than that of i, which has been affected by local fluctuations of liquid water content, least squares regression curves need not be computed. Instead the average value of S, the slope, was computed for each size group and instrument. The calibrations as computed from these average values of S are given in Figures 3 and 4.

Table 1

Maximum and volume median drop sizes for various spray conditions.

(Broken lines represent grouping boundaries.)

Flow cc/min.	Pressure lb/sq.in.	5	10	15	20	30	40	60	80
117	Max	230μ	204	160	135	104	85	65	50
	Med	120	100	80	68	54	44	34	28
174	Max	245	220	174	145	110	95	70	55
	Med	138	122	97	82	66	56	43	36
230	Max	260	230	185	155	120	100	75	60
	Med	151	136	108	92	74	62	48	40
287	Max	277	245	195	165	130	105	80	65
	Med	164	150	120	102	82	70	54	46
414	Max	310	280	220	185	145	123	95	75
	Med	192	184	147	126	102	86	68	58
545	Max	348	310	250	210	165	140	108	88
	Med	220	218	174	150	120	102	82	70

Group 1	Group 2	Group 3	Group 4
Avg. (Max 283	Avg. (Max 195	Avg. (Max 110	Avg. (Max 64
(Med 173	(Med 120	(Med 70	(Med 42

As shown in Figures 3 and 4, S decreases with drop size for the cloud instrument and increases for the rain instrument. From these lines the volume median drop diameter as a function of cloud to precipitation instrument current ratio was found and is given in Figure 5. With either of the calibrations and Figure 5, volume median drop diameter and cloud liquid water may be found from the two instrument readings. First the volume median drop diameter is evaluated from the ratio of the instrument responses. Then the liquid water content is found from either one of the calibrations by the line on the graph corresponding to the volume median diameter.

In the calibrations given in Figures 3 and 4, the errors are practically confined to fluctuations of liquid water content in space and time. The error due to fluctuation of tunnel air speed is at most $\pm 1\,\mu$amp. Therefore, all calibration curves must go through the origin. Some of the error may be the result of neglecting the possible non-linearity and dependence on air speed of the instruments' performance, but as already mentioned these factors were not apparent in the data. Therefore, the error analysis was based on the standard deviations of the slopes S from the averages for each size group. From these standard deviations the percentage errors of the cloud and rain instrument calibrations were estimated to be between 15 and 20 percent. The corresponding possible error in volume median drop diameter was estimated as $\pm$ 45 percent in the vicinity of 90 microns. The standard deviations of S were used to construct the estimated error areas given in Figures 3 and 4. Similarly the upper and lower limit curves in Figure 5 were derived.

The response times of the two instruments have been made amply evident both from wind tunnel work and aircraft use. The cloud instrument response time was found to be 1 sec (the time required to reach 63 percent of its full-scale value in response to a sharp change in liquid water) and is entirely a function of wire diameter. The response time of the rain instrument is more complicated in nature, since its response is conditioned by the ceramic cone as well as the wire size, and was evaluated to be 3 sec. This response time may appear short for a large mass such as the ceramic cone, which is quite apparent in the warm-up time of the instrument (considerably larger than 3 sec); but actually the wire and the ceramic surface immediately under it are most influential in establishing the response time to changes in liquid water content.

The writer's (1965) hot wire system for cloud liquid water measurement constitutes a combination of the hot wire technique with the older aerodynamic winnowing principles developed in connection with the rotating cylinder method. This system constitutes a definite improvement over previous hot wire instruments in that the effect of drop size has been approximately taken into account in its calibration. Although the accuracy of the calibration still leaves much to be desired, the basic procedure appears sound. The calibration can undoubtedly be improved by experimentation with the nozzle array configuration. Also, the calibration should be extended to larger drops by using nozzles without compressed air atomization.

3. Outline of computation procedure.

As already stated, even though part of the data were recorded in analogue form, steps were taken to digitize these data. Empirical equations were fitted to the calibration curves given in Figures 3, 4, and 5. These were incorporated in the Fortran II program for computing cloud liquid water content and volume median drop diameter in deriving the final tapes.

A corrected version of Bunker's method (1957) for computing turbulent vertical air velocity was also incorporated into the above program. The basic error contained in the derivation given by Bunker may not be important in small amplitude turbulence of about 1 meter per second, but in cloud turbulence the amplitude may be large enough to cause large fluctuations in the lift coefficient. In the difference equation derived by Bunker the average lift coefficient is used in the air speed fluctuation term. However, the lift coefficient can change quite radically with a strong vertical gust. For a strong downdraft the lift coefficient could even be negative. The details of the computation are given in the Appendix.

4. In conclusion.

Programming in Fortran II has been carried to a point where "WHOI Stormfury 1965 I and II" tapes may be made. Sample tapes have been made from these programs for the day's work done on August 5, 1965.

In addition, programs have been designed to make averages of the data on the "NHRL Stormfury 1965" tapes over time intervals of 1,000 seconds and 200 seconds, which are intended for use on constant pressure level charts to show synoptic and meso-scale motions, respectively. Some sample analyses of plotted wind data derived from the above programs is given in the writer's final report to the National Science Foundation (1966).

There is still a lot more work to be done with the data. However, the most difficult part of the programming has been completed. The tapes and Fortran source programs are undoubtedly compatible with almost any computer equipped with a Fortran II compiler.

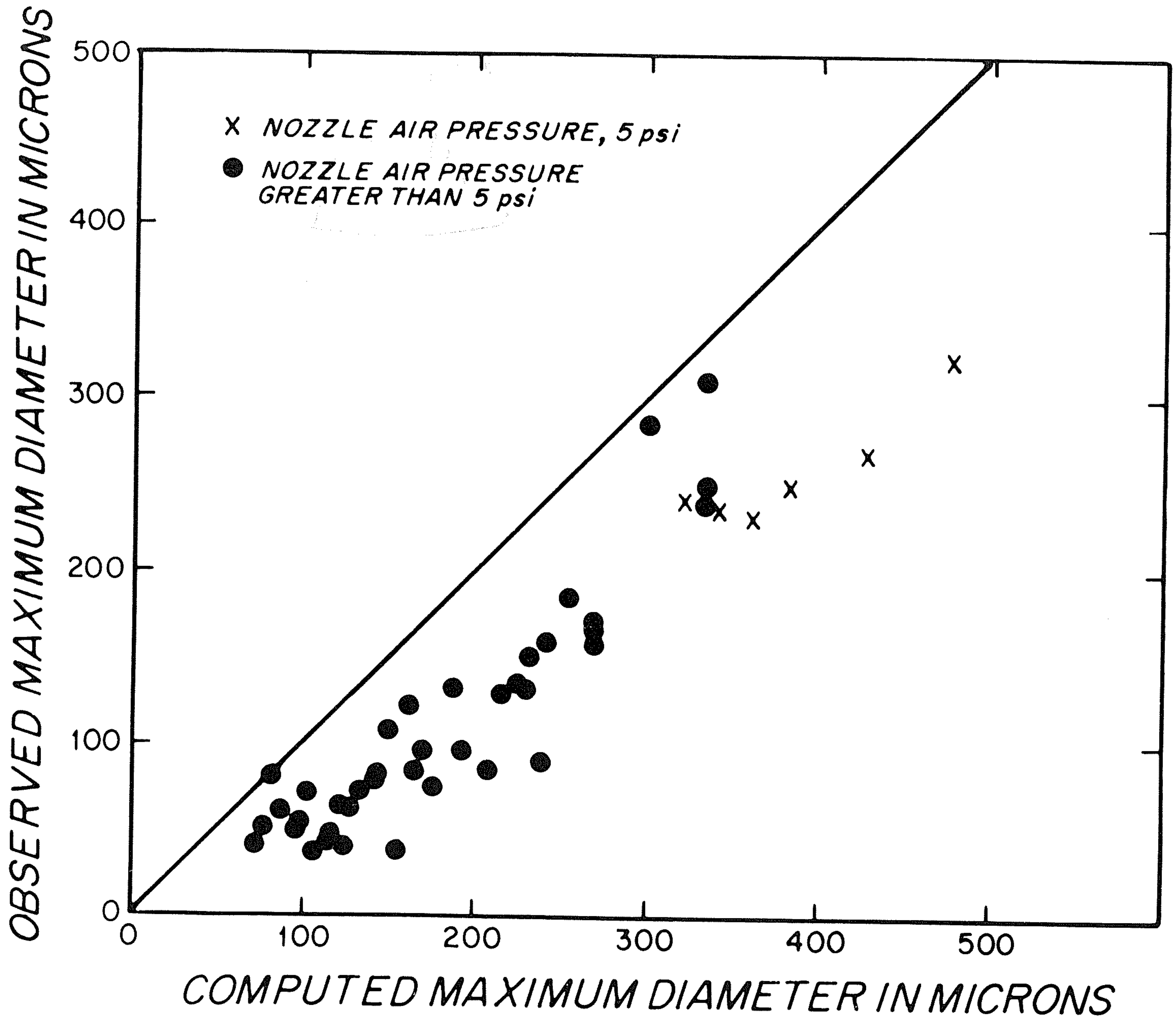

Figure 1. Correlation of measured maximum drop diameter with that computed from empirical equation $2a_{max} = (.8W + 655)/\sqrt{P} - 12$

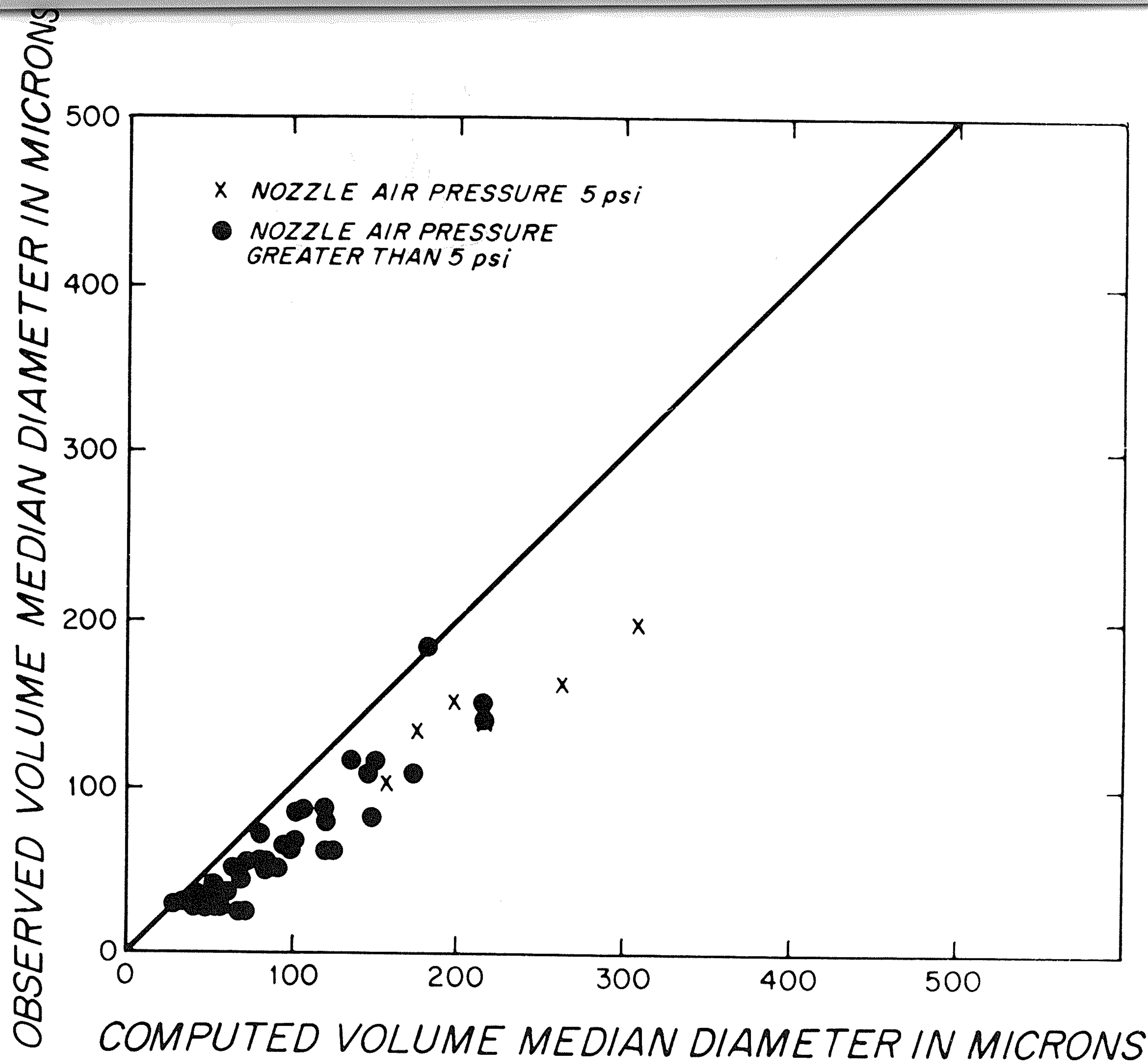

Figure 2. Correlation of volume median drop diameter computed from N_1/N_2 with that computed from empirical equation $2a_{max} = (.8W + 282)/\sqrt{P} - 12$

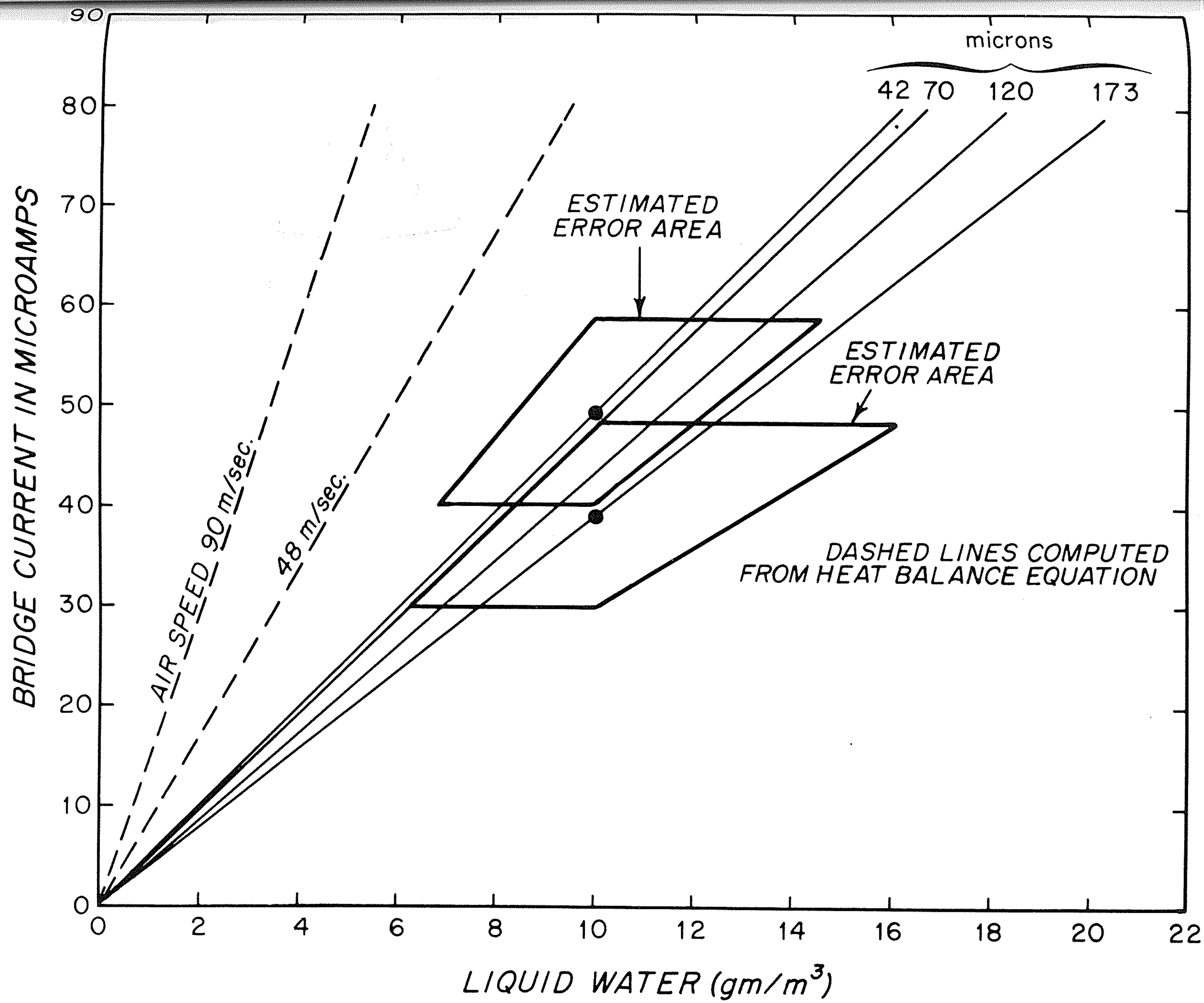

Figure 3. Calibration of cloud instrument over air speed range from 95 to 176 knots. Slides of error areas represent extremes in current and liquid water derived from standard deviation of S for 42 and 173 micron size groups.

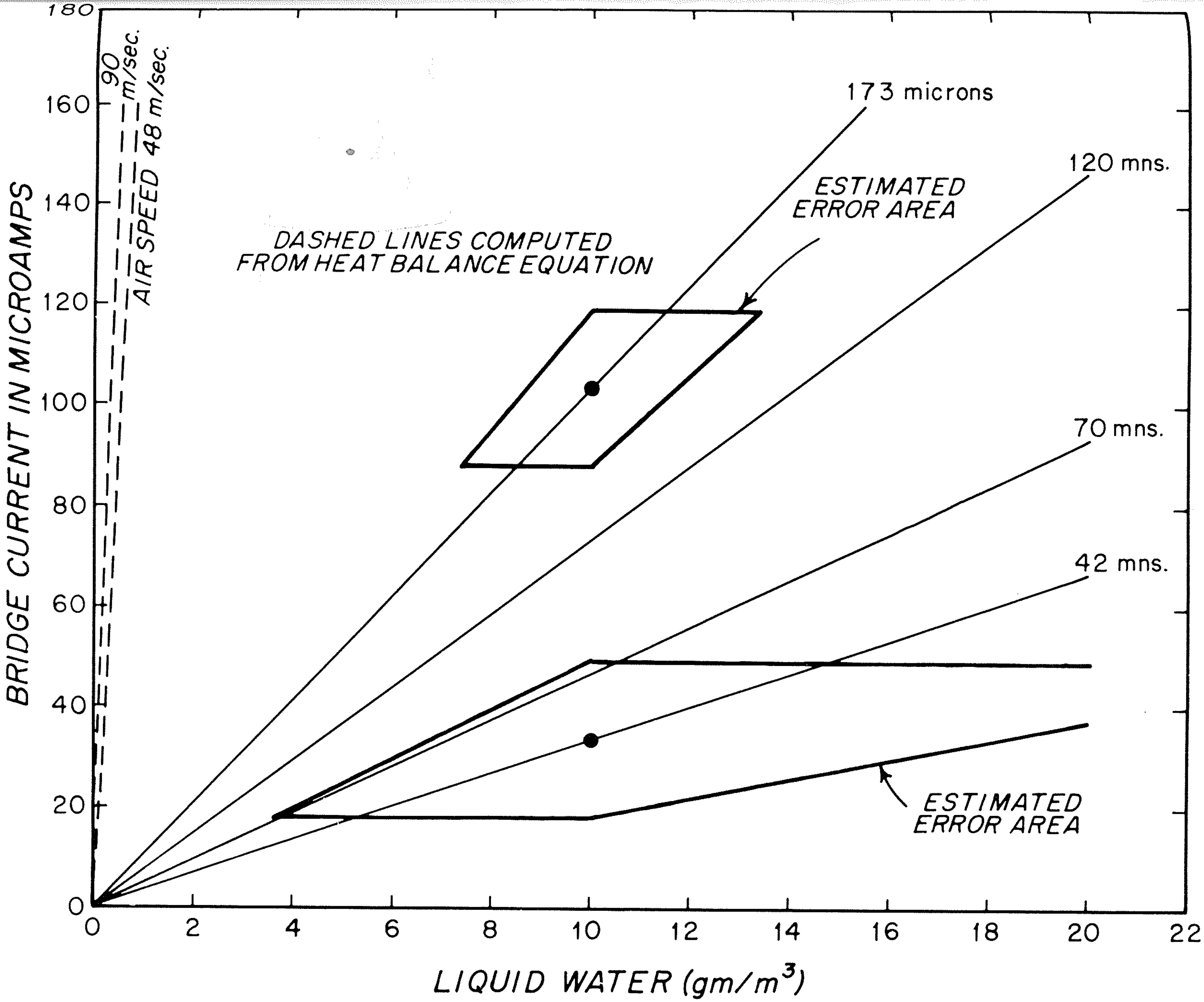

Figure 4. Calibration of rain instrument over air speed range from 95 to 176 knots. Sides of error areas represent extremes in current and liquid water derived from standard deviation of S for 42 and 173 micron size groups.

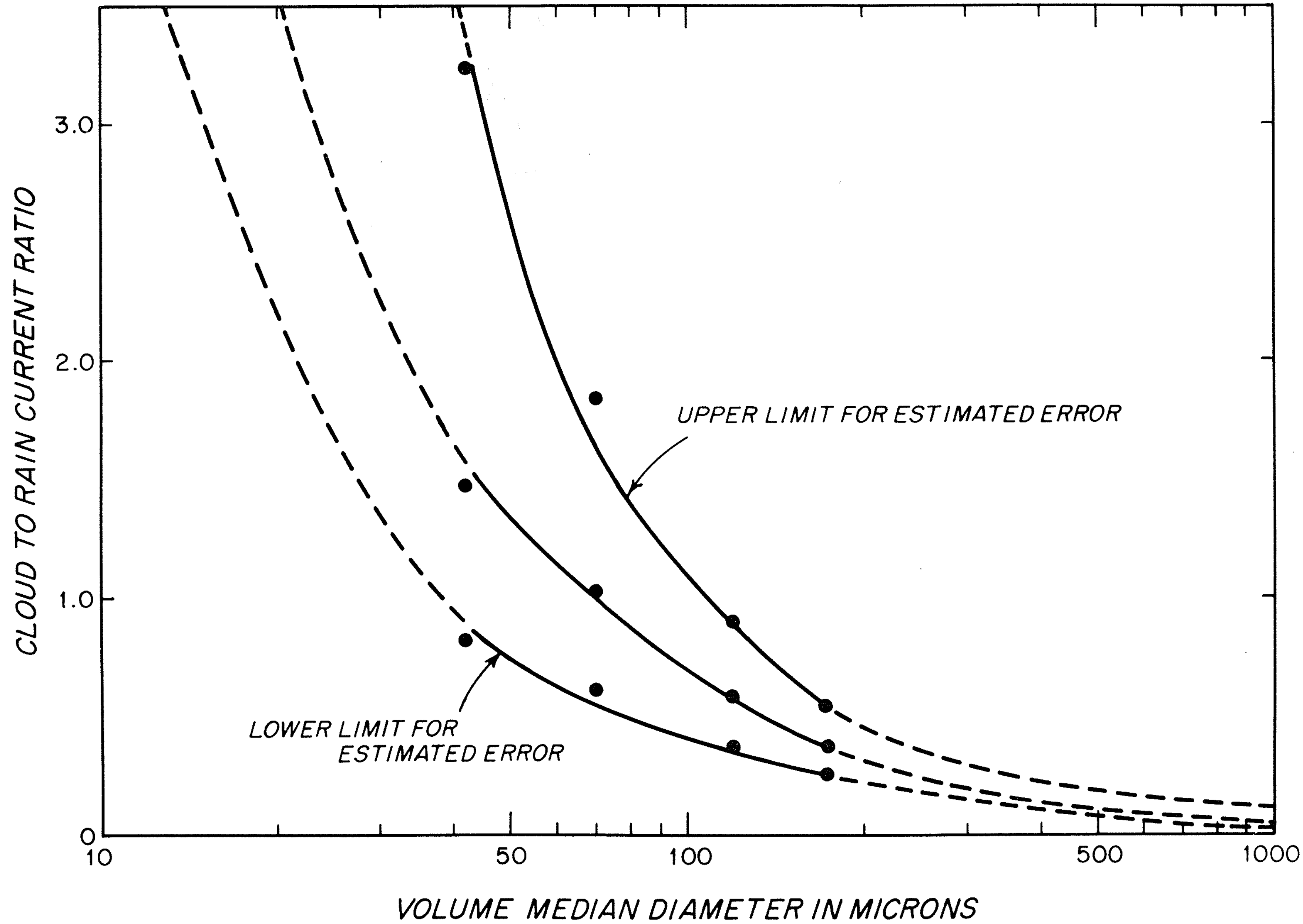

Figure 5. Ratio of cloud to rain instrument bridge current as function of volume median drop diameter. Dashed portions of curves are extrapolated.

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Appendix

Computation of Turbulent Vertical Velocity

The basic algebraic equations are expressed in fortran notation for convenience in relating them to the basic program for making "Stormfury 1965 II" tapes. In using the fortran convention for symbols, there is no longer any danger of running out of letters. The details of this computation are supplied because it represents a significant departure from Bunker's (1957) procedure. Instead of using the difference form of the lift equation (Bunker, 1957) the lift equation is solved for the lift coefficient CL.

CL = 2.*GM*(980. + ACC)/DE*TAS*TAS*WSA (1)

GM	mass of airplane
ACC	vertical acceleration of airplane
DE	air density
WSA	wing surface area
TAS	true air speed

ACC, TAS, and DE are derived from observations. WSA the effective wing area is about $160m^2$, but a more accurate figure may be obtained from the airplane's performance in clear air. The variable mass of the airplane may be approximately taken into account by the equation

GM = 4.86 E7 - 1.14 E6*(HT - BT) (2)

BT	time at start of aircraft operation day (hours and tenths).
HT	time at start of cloud run (hours and tenths).

DE may be computed from observed data by

DE = PM*1000./(2.87 E6* [VTE + 273.]) (3)

PM pressure in millibars
VTE vortex thermometer temperature

$$WSA = 2.*980*GM/DE*TASO*TASO*CLO \tag{4}$$

where the suffix 0 is used to designate the clear air average.

$$CLO = .37 + 5.24*PIRO \tag{5}$$

The vertical velocity of the air by Bunker's angle of attack equations is

$$VVA = (AT - PIR)*TAS + VVAP \tag{6}$$

PIR pitch angle in radians
PID pitch angle in degrees
VVAP vertical velocity of airplane

$$PIR = PID/57.3$$

The angle of attack is in turn

$$AT = (CL - .37)/5.24 \tag{7}$$

VVAP may be computed in three different ways for substitution in equation (6): (a) by taking pressure altitude differences, (b) by taking radar altitude differences, and (c) integration of the vertical acceleration.

$$VVAP1\ (NT) = (PAL[NT + 1] - PAL[NT - 1])*30.5/2.0$$

$$VVAP2\ (NT) = (RAL[NT + 1] - RAL[NT - 1])*30.5/2.0$$

PAL pressure altitude in feet
RAL radar altimeter altitude in feet

$$VVAP3\ (NT) = ACC(1) + ACC(2) + \ldots.ACC(NT) + \begin{cases} VVAP10 \\ VVAP20 \end{cases}$$

The computer program has been designed to compute the vertical velocity of the air from equation (6) by proper substitution from the other equations.

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In addition a preliminary analysis of the meso-scale wind field as derived from aircraft Doppler wind observations taken during one day of the Stormfury 1965 operation is described. Such facts as scale and magnitude of meso-scale divergence and vertical velocity in the trades are inferred.

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